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Selected Papers
from the
BUREAU of
RADIOLOGICAL HEALTH
Seminar Program

ADVANCES in the USE of MICROWAVE POWER

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SELECTED PAPERS from the BUREAU of RADIOLOGICAL HEALTH SEMINAR PROGRAM

FOREWORD

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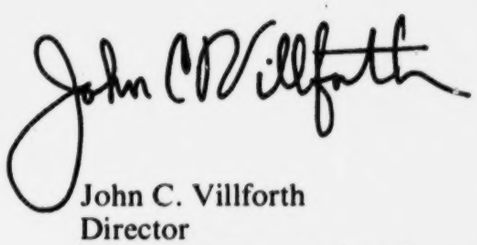
Within the Bureau, the Office of Information disseminates information about the significant events occurring in the field of radiological health. In pursuit of this mission, the Office conducts a program of seminars and symposia. When a presentation is believed to be of especial interest, the speaker is invited to publish in this series entitled "Selected Papers from the Bureau of Radiological Health Seminar Program."

The Bureau also publishes the monthly **Radiological Health Data and Reports,** and special division technical reports. These publications are intended to provide a vehicle for conveying the results of radiological health studies to audiences which have specific interests.

The Selected Papers are distributed to State and local radiological health program personnel, Bureau technical staff, advisory committee members, university radiation safety officers, libraries and information services, industry, hospitals, schools, and other interested individuals. These reports are also included in the collection announced and made available by the Clearinghouse for Federal Scientific and Technical Information.

I encourage the readers of these reports to inform the Bureau of their opinions of these papers and of their value to the radiological health community.



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Dr. Voss was born in Westcliff, England in 1935. He received his college education at Brentwood and Queen Mary College of the University of London before coming to Canada in 1959 on a NATO exchange studentship. He was awarded his Ph.D. degree in Electrical Engineering from the University of London in 1961. Later in 1961, he accepted a position as an Assistant Professor at the University of British Columbia and, in 1964, moved to the University of Alberta as an Associate Professor. He is currently Professor of Electrical Engineering.

In 1966, Dr. Voss established a consulting engineering practice, which is now the firm of Voss, Edwards, Tinga and Associates Limited. This enterprise is engaged in the design and evaluation of electronic processing systems, control circuitry, and instrumentation. He is the Editor of the Journal of Microwave Power, a past President of the International Microwave Power Institute, and a member of several committees which are currently studying new uses of electromagnetic energy.

Dr. Voss lives in Edmonton, is married, and has two sons and a daughter.

ADVANCES IN THE USE OF MICROWAVE POWER[1]

W. A. Geoffrey Voss, Ph.D.

1. INTRODUCTION

The present industrial and domestic use of microwave power is a direct fallout of modern military technology and the space age. Tesla's attempt to transmit power without wires almost sixty years ago is today emerging as a giant new high power microwave technology for transmission at the multi-megawatt power level in small pipes. This technology is emerging for the propulsion of hovercraft, possibly for spacecraft, and for high speed ground transportation as well as several other applications beyond the basic, high speed, deep heating of materials. (31, 27, 7, 8, 4, 2)

It is now technically possible to generate a continuous 1 MW in a single tube structure at microwave frequencies * with efficiencies approaching 75%. (19) Higher efficiencies are possibly (90% for the amplitron structure) and the higher microwave frequencies, presently up to 55 GHz, are being used as a source of power in controlled fusion research. (31, 16) Bechtel Corporation, the largest contractor-consulting organization in the world, has undertaken intensive studies into not only transmission and rectification, but also into the large scale industrial use of microwave energy in the material processing industry and has acquired an intensive interest in the long range economics of high frequency technologies. (6, 21, 13) Some 70 corporations throughout the free world are now known to be manufacturing microwave heating equipment for industrial and domestic use. The rapid heating and reheating ability of a microwave oven is an attractive prospect, not only in industry, but also in the modern kitchen. The domestic and military demand for heat and power have established an attractive tube market and have, consequently, made microwave heating broader and far more significant than the earlier rather restricted markets for induction and low frequency dielectric (RF) heating in the allocated frequency bands. (7, 8, 14) The result has been a rapid increase in the sale of microwave generators and heating equipment in the industrialized areas of the world (as shown in Figures 1 and 2) for a wide range of uses in the food service industry as well as other industries. Table 1.1 shows the specific frequencies currently allocated for these non-communication uses and Table 1.2 attempts to identify the major areas of industrial interest and use up to the end of 1968.

All this, to quote William Royce* of the Stanford Research Institute is indicative of the noise before the real development curve begins. Microwave processing is a technology fraught with both opportunities and problems, many of which were discussed and foreseen by Cable in 1954. (9) However, the development has gone far enough and the signs of industrial acceptance are great enough to cause a challenge to the microwave engineer and the processing system's designer. This development and subsequent acceptance should also result in a general interdisciplinary concern to learn more of the biological effects in order to determine the

*The microwave frequency range is that part of the spectrum between 100 MHz and 300 GHz (3 meters to 1 millimeter in wavelength). 1 Hz = 1 cps; 1 MHz = 10^6 Hz; 1 GHz = 10^9Hz. Microwave power is either pulsed or continuous wave (CW), the latter being the case for the majority of noncommunication applications. Thus 1 MW(CW) designates a continuous output power of one megawatt, or 10^6 watts.

[1]This paper was presented as a part of the Bureau of Radiological Health's Seminar Program on April 25, 1969, in Rockville, Maryland.

*Speaking at Varian's first seminar on the industrial uses of microwave power, San Mateo, Cal., January 1968.

TABLE 1.1 INDUSTRIAL, SCIENTIFIC AND MEDICAL (ISM) BANDS

	ALLOCATED FREQUENCIES	WAVELENGTH
Radio Frequencies:	13.56 MHz ± 0.05%	22.1 m
	27.12 MHz ± 0.06%	11.1 m
	40.68 MHz ± 0.05%	7.4 m
Microwave:	433.92 MHz ± 0.2%	69 cm (b)
	915 MHz ± 25 MHz	32.8 cm { Western Hemisphere (c)
	2.45 GHz ± 50 MHz	12.2 cm (d)
	5.8 GHz ± 75 MHz	5.2 cm
	17.85-18.15 GHz	1.7 cm (U.S.A.)
	22.125 GHz ± 125 MHz	1.4 cm

(a) International Telecommunications and Radio Conferences, Geneva, 1959.

(b) In Western Germany, Austria, Portugal, Yugoslavia and Switzerland,

(c) or parts thereof, in Europe. 896 ± 4 MHz in Great Britain.

(d) Exept in Albania, Bulgaria, Hungary, Poland, Rumania, Czechoslovakia and the the U.S.S.R. where the frequency of 2.375 GHz is used.

(e) For further information, see RCA: Frequency Allocations, (1965)

hazards of high frequency, non-ionizing radiation and in so doing, establish the necessary guidelines for design and control.

The challenge and opportunity for microwave energy is not confined, in terms of modern technological ability, to the ISM bands any more than it is confined to industrial processing. Its growing interest to the research worker, in many different disciplines of science and engineering, arises from gains which can be acquired from the use of electronic power and heat in terms of pollution and environment control. The use of fossil fuels has to decrease. So do working hours. Electric power, derived in the future from the sun by means of microwave transmission to a point on the earth from satellites in equatorial orbit is, perhaps, one possible solution (Glazer,

TABLE 1.2 MAJOR AREAS OF UTILIZATION

ABBREVIATIONS USED

A (915 MHz), B (2,450 MHz): Production Systems
a (915 MHz), b (2,450 MHz): R & D Systems, Pilot Studies
e,E: At higher frequencies (e': 5.28 GHz, e": 8 GHz)
C: Institute research at a, b, e, etc.
D: Active RF industry.

FOOD INDUSTRY

Potato chip final drying (A,B); Bacon pre-cooking (A,B); Donut proofing (a,B); Factory reheating of foods, etc. (A,B; mainly B); Restaurant ovens, vending machines (A,B; mainly B); Freeze-drying (a,b); Military field stations (B); Chicken cooking (B,a); Sterilization, pasteurization (b); Fruit preparation (A,b); Nut roasting (B); Biscuit manufacture (D,a,b)

FOREST PRODUCTS INDUSTRY

Hardwood drying (B); Softwood veneer redrying (d,a); Veneer drying (D); Softwood lumber drying (a,b); Specialized paper products (a,b); Paper drying (D,C,b); Overlays (b); Coatings (a,b); Glues, etc. (b); Newsprint drying (B); Special products (shoe lasts, golf heads, etc.) (D,B)

PLASTICS INDUSTRY

Epoxy pipe curing (B,a,b); Extrusion processes (D,b); Polyesters, epoxy resins - specialized products (D,b); Sealing of plastics (B,D)

MINING INDUSTRY

All (b); Rock crushing, concrete curing and cracking. Coal by-products (A,b); Oil extraction (b); Diatomacious earth drying (C,b)

CHEMICAL INDUSTRY

Drying in general (b); Chemical products through plasma generation (b)*

AUTO INDUSTRY

Foundry core drying (B,D); Urethane foam curing (B)

DRUG INDUSTRY

Drying (a,B,e',e") - particularly temperature sensitive materials and sub-equilibrium drying

GENERAL

Leather drying (b,C); soap preparation (b); Grain drying (b); Insect control in grain (b,C); Cocoon (silk) drying (B); Yarn drying (B,e',e"); Diathermy (D,B,A)

*Largest area of research interest.

1968). The danger is that we would then be trading one form of pollution for another.

In 1966, when the International Microwave Power Institute* (IMPI) was founded with the object of promoting an understanding of all aspects of microwave power, microwave energy was the most expensive form of heat ever considered in the food and forest products industry, but its use, in general, was increasing. It was predicted at the first symposium that by 1970 generation costs would be little higher, if the industry developed, than those at the lower radio frequencies. Today we can see this coming true; we see the essential investigations into equipment performance and cost as they arise in use, and some successful production systems. The necessary environment control and safety will follow from the invaluable work of Suroviec (1967), Breysse (1969) and others. An investigation has been undertaken by Crapuchettes (1969) into the methods and problems associated with measuring leakage power. Instruments for this purpose had previously been reported to be unsatisfactory (Miller and Sheftman, 1961). New types are now available. Development work in measurement techniques is apparent and the Radiation Control for Health and Safety Act (Public Law 90-602) is an important stimulus to research work on the biological effects of high frequency energy. Studies in the Bureau of Radiological Health (BRH) are vital for the public safety and my job in this paper is primarily to discuss design techniques. This discussion will include factors involved in the safe use of microwave energy as it advances into more and more aspects of our lives.* It will take into account that equipment is increasingly being sold in such a manner that it is beyond recall and that it is being serviced in many cases by the local television repairman, who, at this time, does not know what he is doing.

*Membership in the Institute is open to anyone with interest in microwave power; IMPI has published the Journal of Microwave Power since 1966. International Symposia are held annually: 1966 (Edmonton), 1967 (Stanford), 1968 (Boston), 1969 (Edmonton), 1970 (The Hague). Information can be obtained by writing to IMPI, Station D, Box 4204, Vancouver, British Columbia.

2. GENERATION

Conversion of electrical power to microwave energy has improved, in magnitude (KW per structure), efficiency, and cost during the last few years at a faster rate than was anticipated in the early 1960's. Weight, size, and reliability have also improved; a 25 KW magnetron at 915 MHz now has a probable life of 10 Khrs, costs presently only five times its estimated ultimate production value of $500, can be held easily and inserted quickly by one person into a waveguide launcher. In modified form, the structure could reach an efficiency of 90% and is currently above 75%. Prototype structures of approximately the same size are now operating at twice the commercially available output power. The true generation cost of microwave energy, which must include the amortization of the tube, is ultimately 0.2¢/KWhr and presently ranges from 5¢/KWhr for small tubes (microwave ovens) to 1¢/KWhr for the larger structures. The ultimate figure, as would be expected, applies to all frequencies within existing technological limits, and is presently achieved at 500 MHz and below with conventional radio frequency tubes, whose use is also increasing.

A rather general law, involving a technological constant, k, is often given to describe the power output capability of a single tube structure at a given frequency;

$Pf^2 = k$ or $Pf^{3/2} = k$, the former being the more likely. Today $k \approx 30 \times 10^{24}$ Watt-herz^2; thus if 1 MW(CW) is now commercially available at 2.5 GHz (slightly above this is technically possible), just over 2 KW should be possible at 55 GHz. In fact, 5 and 10 KW

*A two-volume series, "Microwave Power Engineering" (Ed.E.C. Okress, Academic Press, 1968) consists of contributions from authors all over the world on the generation, transmission and utilization of microwave energy. Vol. 2, "Applications," illustrates the wide spectrum of systems and evaluation programs underway. Two other books contain a wealth of information: "Heating with Microwaves," H. Püschner, (Springer Verlag, New York, 1966) and "Microwave Heating," D.A. Copson (Avi, Westport, 1962), the latter being mainly concerned with food processing.

tubes at this frequency are in limited use (Eason, 1969).

In more general terms, man's ability to generate electromagnetic power into the atmosphere is increasing at more than an order of magnitude per decade (15 decibels) and our ability to use and convert microwave energy from a source, to heat (for processing) and d.c. power (for rectification) is rising faster; however, rectification technology is in its infancy (Okress, 1968, Vol. 1, p. 340; Ishii, 1969), but its importance, particularly from a military point of view, is very great. (46)

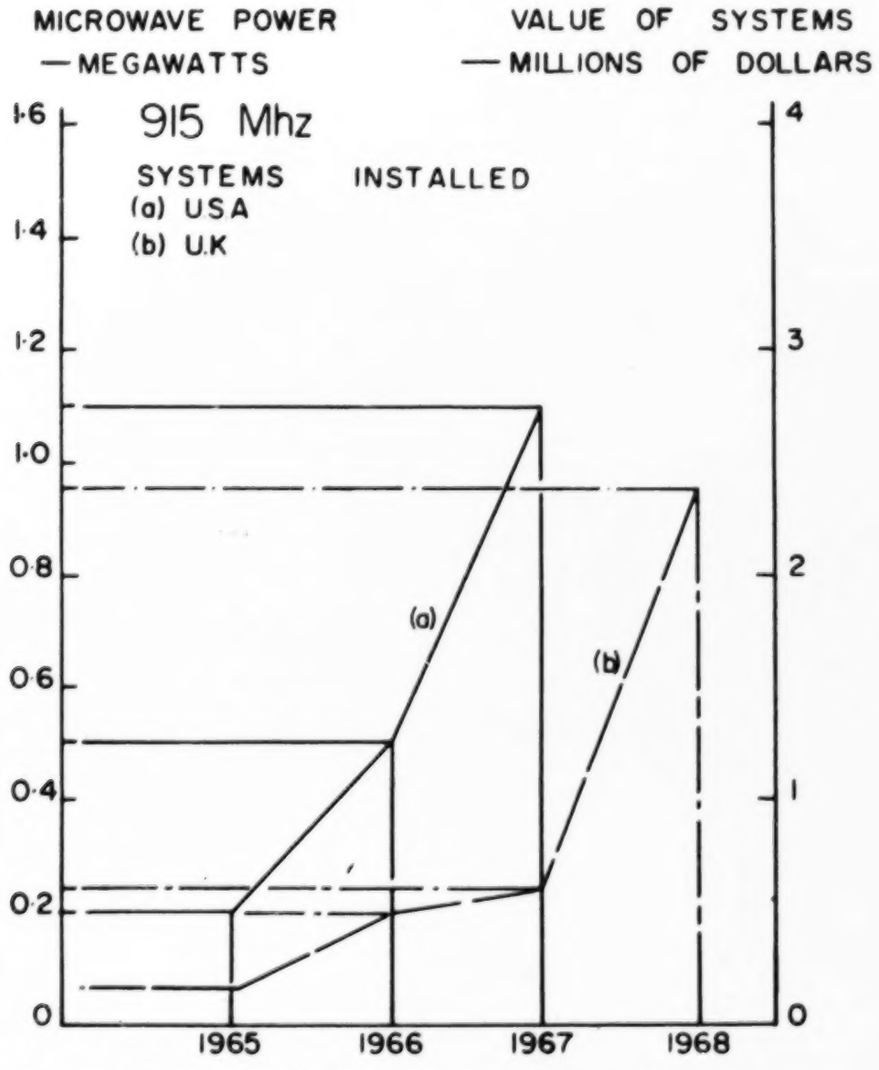
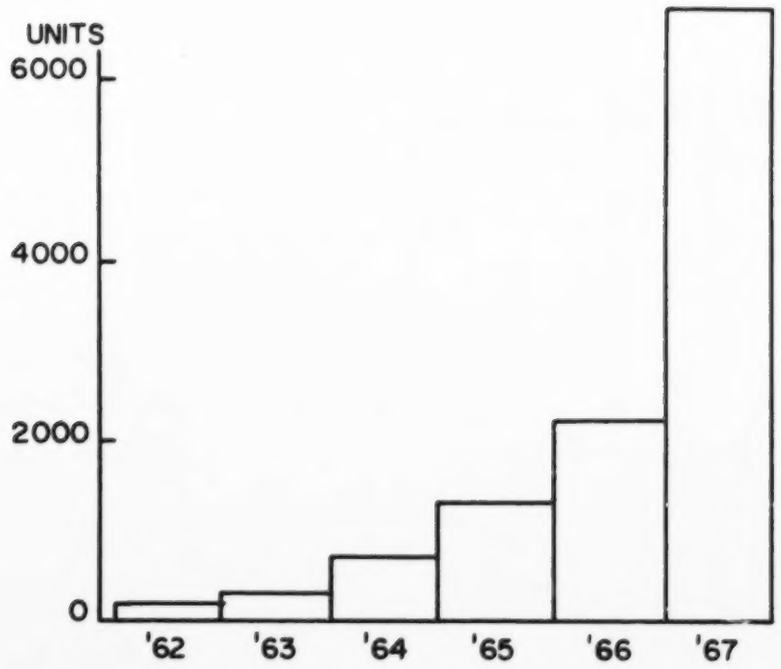


Figure 1. The growth of 915 MHz industrial microwave processing.
The module size is 25 KW.
(Source: Jeppson, 1968, and Voss)
In addition to these systems, of which more than 80% are in the food industry, an estimated 10,000 small microwave ovens at this frequency are in general use for cooking and reheating foods. The module size is 800 watts in this case. Estimated total 915 MHz generation capability (domestic and industrial) 10 MW by 1969, having risen from 0.25 MW in 1965.



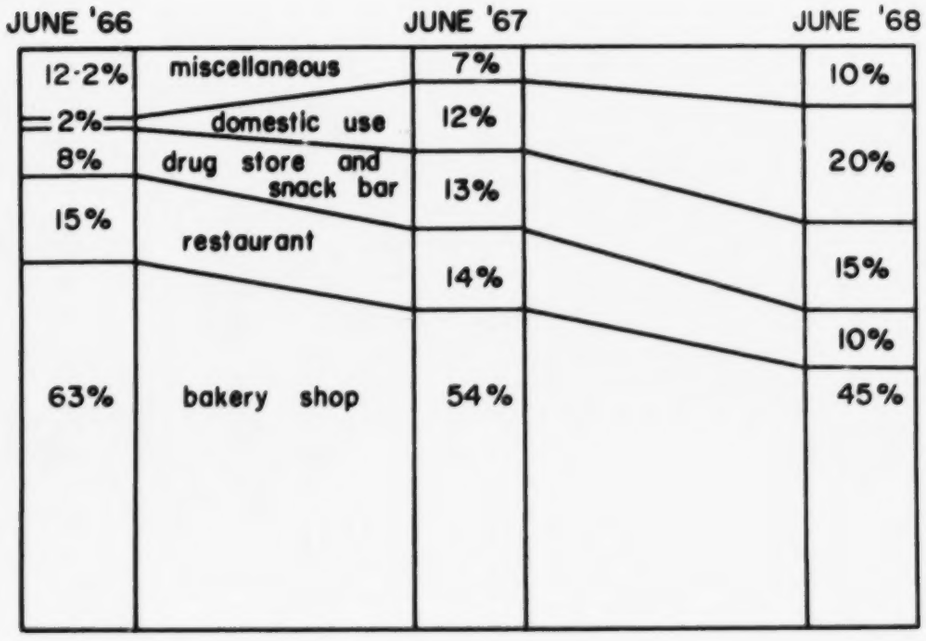


Figure 2. The rate of increase of acceptance of the small (0.4 to 2 KW) microwave ovens was large in 1967 and 1968.
(Source: Sasaki JMP 3(2), p86, 1968). The trend is the same in Scandinavia and the United States. Total installed power is estimated at 200 MW, in the free world, at the end of 1968. The domestic use has increased from an estimated 10% (1966) to 20% by 1969, with a projected 85% value by 1975. In highly industrialized countries, the writers project that more than 60% of all apartment dwellings will have a microwave oven by 1980. Ensuring public safety is now of paramount importance: good design with foolproof interlocks, availability of experienced and qualified service personnel, with clear guidelines and adequate leakage detection devices, are vital factors.

The most powerful generation systems are not necessarily the most efficient; at the lower frequencies (below microwave) the negative grid tube, with a 25 to 70% efficiency, is cheap and simple. However, its usefulness falls off at or below the first microwave ISM band, where the magnetron takes over for small systems, and the klystron for larger ones. Equation 1 applies to the optimum known structure. Table 2.1 attempts to summarize the present CW tube situation, being confined to those tubes in use.

Generation efficiency is a function of output power. It is generally uneconomic to run generators at a varying output level; consequently many systems, particularly those where the heating requirements change with load, use several tubes and thus several generator modules. A required power of, for example, 30 KW at 2.45 GHz can be obtained with one klystron, 30, 15 or six magnetrons. Considerations of reliability, power control, and equipment cost dictate the final choice. Designers are generally constrained to the range of one to five modules. However, up to 60 generators have been used in one system (chicken cooking), 10 is not uncommon, and two is usual (potato chips, etc.). Some domestic microwave ovens even use two tubes. This approach results in increasing both the reliability and uniformity of heating. At 915 MHz, because of lack of low power tubes, experimental systems are forced to use 25 KW magnetrons; although the small magnetron at this frequency can be very cheaply made (about $25 per KW), it is currently sold only as a sealed power supply in an oven system.

Some of the tubes' inefficiency arises from leakage into the surrounding space (typically 50 watts from a 2 KW magnetron at 2.45 GHz) and generator shielding is essential to prevent a hazard, as well as harmonic interference into other bands. Experimenters are all too unaware of the hazard of exposed magnetron cathodes.

The klystron, suitable for higher powers, is by far the most versatile generator. This year its efficiency became comparable to that of the high power magnetron. In sophisticated CW applications, industrial as well as military, the klystron will probably become the dominant tube; however, the magnetron is capable of operating as a crude, but quite efficient, "rotary converter." Not only can high voltage d.c. power be fed directly to it, but both rectified and semi-rectified a.c. from 13 KV transmission lines can also be used. Thus Grimm* envisions the eventual direct power-pole conversion for industry at very little capital cost. This has been attempted and could eventually open up an unsophisticated "brute-force" source of electronic energy at a frequency of considerable interest to primary industry.

In no previous year has the advance in commercial microwave power generation been as great.

3. TRANSMISSION: THE APPLICATOR

There are basically two types of applicators: resonant and travelling wave. These take the form of cavities and waveguide arrays. Free space and nonresonant antenna applicators which are similar to radar horn antennae are used experimentally. Specific designs of these applicators are used in the form of over-moded waveguides for food reheating (Philips, 1966 - see Püschner, 1966, Section 8). A hybrid type, called either a leaking slot, a fringe field or a bar radiator, is used in specific cases (e.g. blood plasma warming - Püschner, 1966, p. 144; kiln preheating of lumber - Williams, 1969). An almost limitless number of designs is possible and, as the necessary applications arise, metal pipes (Aluminum or stainless steel) will be designed to "shape" the field to the material. All the technical developments of radar are available to the power engineer. The great advantage of microwave heating lies in the compatability of the required applicator sizes to existing systems and to the materials which require high speed heating. At 915 MHz, as will be

*Private communication, A.C. Grimm, R.C.A.

TABLE 2.1 INDUSTRIAL MICROWAVE POWER TUBES IN USE

Frequency (MHz)	Type	Efficiency (%)	Life Expectancy (10^3 hrs)	Anode DC Voltage (KV)	Commercially available Power Levels (KW)	Manufacturers	Major use
915	M(S)	75 - 83	2.5(W),5-10	12 - 14	25, 35 (50)	RCA, Varian, EEV, (Raytheon)	1
	M (C)[3]	67	2.5(+)	12 - 14	18 [1]	GE	1
	K	50 - 75 [2]	10(W), 30 +	25 - 30	50 - 100	Varian (for details see Giebler, 1969)	1
	T [3]	25 - 30 +	1 - 5	0.6	0.9, 2	RCA	0
	M(P)	55(-)	-	0.6	0.750 [4]	GE (Stoats, 1968)	0
	M(P)	65	-	5	(5)	Not available but developed, Nelson, (1956)	
2,450[5]	M(S)	50 - 60	2 - 10	3 - 6	2.5	Litton, etc.	0, 1
	M(P)	40 - 60	2 - 10	4 - 6	1, 2, 5	Philips, Amperex, Microwave Energy, American Microwave, etc.	0, 1
	M(P)	-	-	1 - 3	<0.8	Many, particularly Japan	0
	K	50 - 75	10(W), 30 +	28	30, 100	Varian	
5,800 +	K	50(75)	10 +	-	1	Varian, [6] (at higher frequencies as well as above: Hughes, Watkins Johnson.)	

Abbreviations: M = Magnetron, K = Klystron, T = triode [7], S = separate (d.c.) magnetic field, P = permanent magnet.
W = warranty, prorata to use. I = industrial, O = small oven (domestic, restaurant, etc).

(1) Reflection protected, twin output; (2) Higher value now achieved; (3) Available in large quantity orders only for the present; (4) As used in ovens, tube apparently not available as a separate item; (5) A great many tubes are in use; the values given are generalized; (6) Several communications' tubes are in use experimentally for heating; (7) The magnetron is one crossed-field device; klystrons are linear beam tubes.

illustrated in the following paragraphs, efficient transmission in a closed system is achieved typically in 5″ x 10″ rectangular pipes (4″ x 12″ at 2.45 GHz) and several GW could be transmitted in a circular waveguide of comparable dimensions at 3 GHz, if required. At the lower RF frequencies, the closed waveguide becomes impracticably large and parallel wire (open) lines or capacitor electrodes are required. A typical domestic oven resonates in a substantial number of modes at both 2.45 and 0.915 GHz (James, et al., 1966), but would not operate at all below 0.2 GHz.

A further microwave advantage arises from the absorption characteristics of materials; water, for example, with an anomalous dispersion peak at 22 GHz, is a prime absorber of energy in the 1-3 GHz range, representing a workable compromise between penetration depth and uniformity of heating. Efficient and selective deep heating can be achieved in the low frequency microwave range with standard sizes, as illustrated in Figure 3 for an industrial fluid-bed dryer (Allan, 1967).

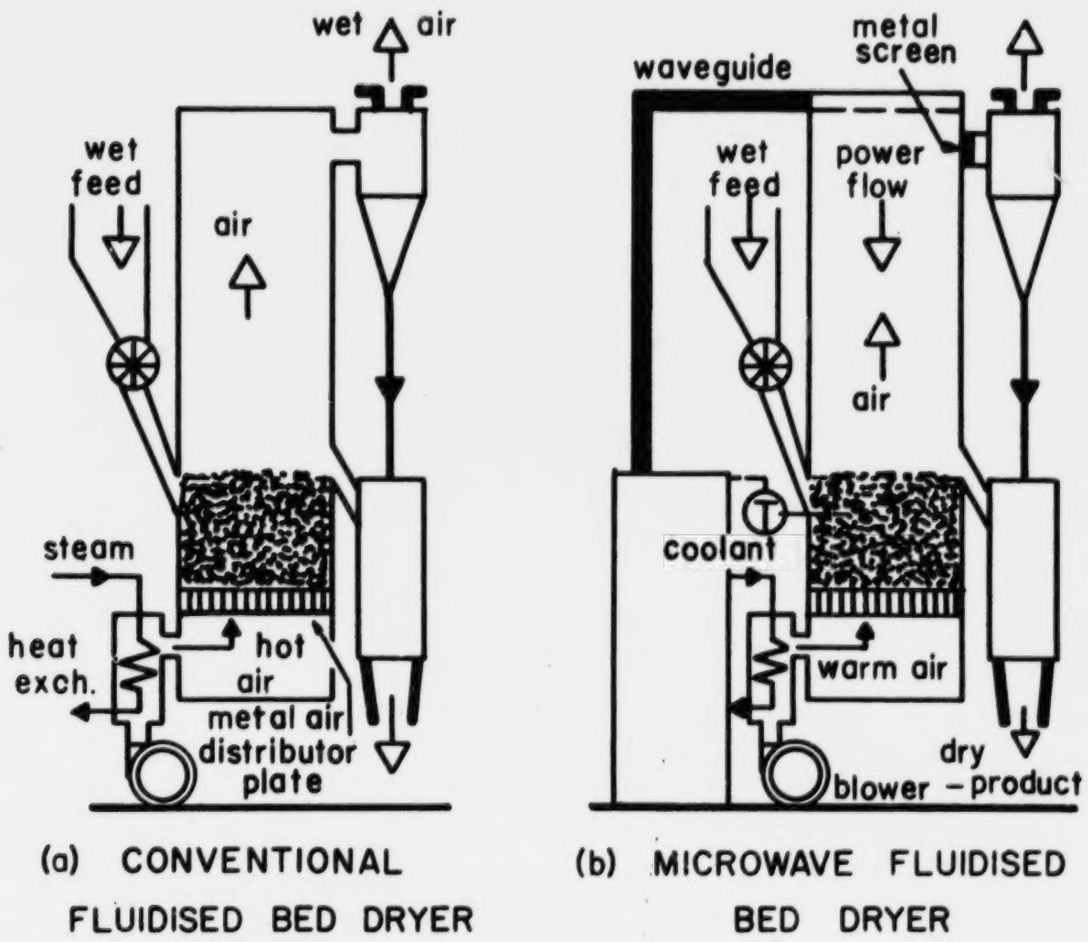


Figure 3. The size, compatibility of microwave multimode cavities (ovens) and conventional drying systems is an important factor to the development of microwave heating. Microwave drying of granular materials has been studied by G.B. Allan (M.Sc. thesis in Electrical Engineering, University of Alberta, 1967; JMP 3(1), 1968) who considered fluid bed techniques. Generation cost of the microwave energy is considered the only limitation to mass use of the techniques illustrated in this schematic drawing by Allan.

The resonant applicator in its simplest form is the domestic microwave oven, illustrated in Figure 4. An actual oven, incorporating some of the best features, in particular a safe door design, is shown in Figure 5. A short transmission line feeds the tube to the resonant cavity. Various power coupling systems are used. They range from coaxial loops into the cavity to arrays of slot couplers from the transmission line. The air system, in order to keep the oven dry and to aid the heating, has to be an integral part of the cavity design. Mode stirrers, coupling systems, and rotating tables are used to achieve uniformity of heating. In small ovens (typically 10" to 15" cubes) uniformity of heating is the major design problem. The number of resonant modes, which determine the spacial distribution of the electric field within the oven, is increased by rounding the metal corners. An unsmoothed d.c. power supply causes the tube to generate power over a significant band width (about 10% of the ISM band) which further improves the number of resonant modes excited (James, et al., 1966). Energy not absorbed in the product is either reflected back to the generator or absorbed in the walls of the cavity which, in the absence of a hot air system, remains cold. Infrared heating elements reduce the efficiency of the microwave source (an additional (rough) surface absorbing power), but are often essential to maintain a surface temperature in what is the reverse of the normal temperature gradient in heating a material.

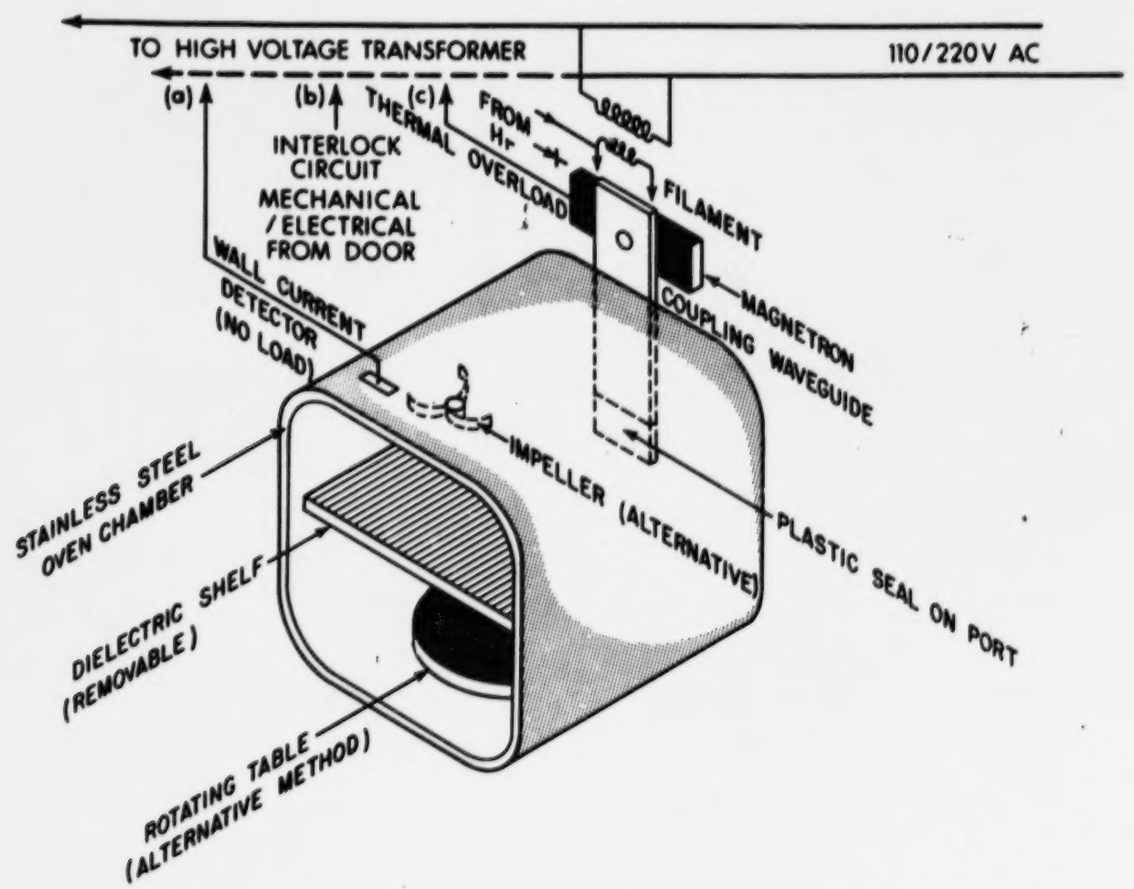


Figure 4. Schematic layout of a small microwave oven, showing (a) the interlock and protection features, and (b) the different methods of achieving uniform heating in a small cavity.
The number of resonant modes (or field configurations) is increased by such techniques as rounding the corners, using cubic dimensions (optimum mode degeneracy) and varying the field pattern with a metal mode stirrer.

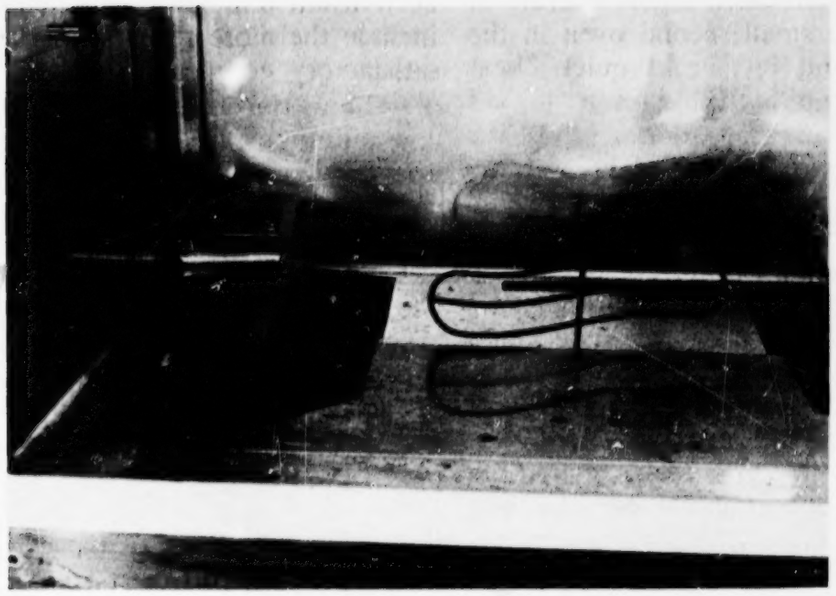


Figure 5. A large microwave oven for domestic and restaurant use, (a) showing the rotating mode stirrer and twin feed-ports (b) the shelf, recessed door, and spring-loaded hinge.

The majority of batch ovens operate at 2.45 GHz; for the small second oven in the modern kitchen and restaurant quick "heat and serve" applications, this is a logical choice. However, the penetration depth of the power is far greater at 915 MHz and the combination oven (e.g. G.E.'s Versatronic range) at this frequency has many desirable features. Allowing for the differences in the dielectric properties at the two frequencies and the effect of frequency, the penetration depth (defined as that depth at which the surface power has been reduced to 1/e of its initial value) is typically five times greater at 915 MHz than at 2.45 GHz. For both frequencies the oven market is highly favourable. The small Japanese (400 watt) ovens are reportedly leaving Japan at $150 each and the U.S. sales may soon reach one half million a year.*

The results of a survey by the Consumer Research Center on the acceptance of microwave ovens also indicate a potentially large future sales volume. This survey has been reported in the trade journal Appliance Manufacturer (July, 1968: "Experience with microwave oven sells owners on this method of cooking"). The major conclusions of this report were that the average period of experience was 3.13 years; the majority of people owning them were in the older age group, and half the total number of ovens involved had been installed in new homes. The study did not include the more recently marketed, and less satisfactory, counter top oven.

Industrial resonant systems with input and output feedports, as well as inspection doors, range in size today from 1 to 10 KW (research units and units being market-tested) at 2.45 GHz and from 5 KW (very few) to 50 KW at 915 MHz. At least two plants in the U.S. have installed units with power levels in excess of 250 KW. One of these operated at 915 MHz and the other at 2.45 GHz. Typical systems are well illustrated by Okress (1968, Vol. 2 - ovens: pp. 7-11; conveyorized units: pp. 21-26, 69; travelling wave dryers, pp. 148, 162, 166). Large resonant systems for industrial processing tend to have low Q cavities and tend to utilize systems of cavities; that is, the field strength is low and the number of modules can be varied. With distributed slot radiators feeding a cavity, the power is absorbed in the product as it travels along the tunnel, leaving little to be reflected from a wall. This is not true, however, when the tunnel is empty or when there are gaps in the product feed.

Sources of leakage arise from doors, feedports, and venting systems. To prevent a health hazard, wave trapping and other protection techniques are required to cover all conditions under which the equipment can be operated. Although the field strengths are low compared to RF, fires can arise and can be severe, particularly if foreign objects are introduced into a system. A lead pencil is a good example of a foreign object which might cause a fire.

A small travelling wave dryer is shown in Figure 6. This unit consists of a series of rectangular pipes feeding power across a material. The power decreases exponentially along the path of the wave, according to the dielectric properties of the material and, as explained in the caption, balancing (uniformity of heating) is achieved by feeding the power from both edges of the material.

Rectangular pipes will transmit microwave power provided the wavelength is less than twice the greatest dimension (note a in

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***A portion of the statement of Mr. J.G. Terrill, Jr., former Director of the National Center for Radiological Health, (currently the Bureau of Radiological Health) presented at the hearings before the Committee on Commerce, United States Senate, Ninetieth Congress, Second Session on S.2067, S.3211, and H.R. 10790. Part 2, Serial No. 90-49 dated May 6 and following, 1968, p. 517 states, "The U.S. Bureau of the Census listed 500 firms in 1965 which were engaged in the manufacture of microwave equipment. The industry employed 420,000 people with sales of 190 million dollars. This list did not include consumer type products; however, four firms were listed as manufacturers of microwave oven equipment for consumer sales. It has been estimated that total sales of microwave ovens for both commercial and consumer use is approximately 40,000 units per year. These units have an average cost of approximately $650.00 each. Reliable estimates indicate that the volume of sales is dependent upon unit cost. Should the price drop to $350/unit, sales could increase by 20,000/year, and at a cost of $250/unit, the sales might exceed 500,000 per year."**

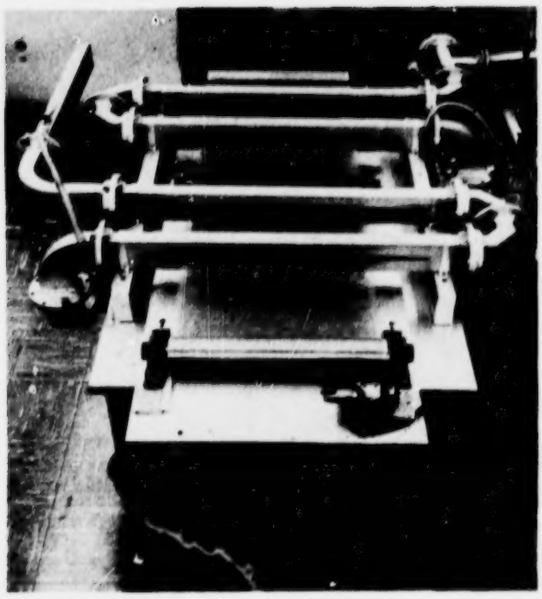

Figure 6. A balanced, low power (2 KW) travelling wave (rectangular waveguide) dryer at 2.45 GHz. Protection screens are not in place (see ahead). The power travels across the material, twice from each side, the remainder being absorbed in two water loads. The power divider is a "T" junction (upper right) from the generator feeding one pair of applicator sections in a counter-flow sense from the right, the other pair from the left in the direction of material flow. The applicator arms (waveguides) are spaced apart in this case to allow for the use of experimental air jets onto the material. The protecting screen is removable to allow for leakage tests with different materials (U. of Alberta, Edmonton, Microwave Power Laboratory).

Figure 7). Thus λ critical = 2a and, as $\lambda f = c$ (the velocity of light), the frequency must be greater than c/2a for propagation to occur. Providing $c/2a < f < c/a$, then only the dominant (TE_{10}) mode propagates for a waveguide whose width to height ratio, b/a = 0.5.* The induced wall currents are at right angles to the lines of the magnetic field, as shown in Figure 7. A slot can be cut in the waveguide in the middle of the broadside wall without disturbing (or greatly perturbing) these wall currents. Material fed in through the waveguide in this way passes through the plane of greatest electric field strength and consequently receives the greatest heating without the mode of propagation. In fact, up to one-third of the side wall can be removed. As illustrated in Figure 7, lips are used to minimize leakage since some energy does propagate (radiate) into the surrounding space. This leakage increases when the material passes through the slot, and the electric field distribution in the dielectric-loaded waveguide is modified as shown in Figure 8. Careful lip design is used to avoid as many undesirable effects as possible; power is reflected at the edge and leaks out both sides. If the material is sufficiently heavy, the dielectric material becomes the waveguide, the metal walls could then be removed and the system would take the form of a shielded cavity, as illustrated in Figure 9.

The sinusoidal E field distribution is compressed into the material and the hazard region expands outwards as the dielectric weight increases (See Figure 10). This expansion can occur due to local effects on materials and, for safety purposes, double shielding (lips and screen) are required, as well as field measurement and specific modification, if required, for each material.

Propagation in a dielectric (i.e. between dielectric-air boundaries) is illustrated in Figure 11. The waves between guiding boundaries may be considered as trains of plane waves reflecting from the interfaces in terms of a critical angle, θ_c (Ramo and Whinnery, loc. sit., pp. 388-393).

In waveguide applicators, which are balanced for uniform heating by feeding power onto both sides of a web material, as explained, leakage is greatest when the system is operating. External shielding is essential and, in production systems, the external casing,

***In the conventional designation of mode types, TEmn or TMmn, the cut-off wavelength for both is given by $\lambda c = 2ab/\sqrt{(mb)^2 + (na)^2}$ Decreasing the dimension b does not alter λc for the dominant mode (m = 1, n = 0) but does increase the electric field strength for a given power transmission (see, for example, Ramo, S., and Whimery, J.R. (1953) Fields and Waves in Modern Radio, Wiley, New York, pp. 366-74).**

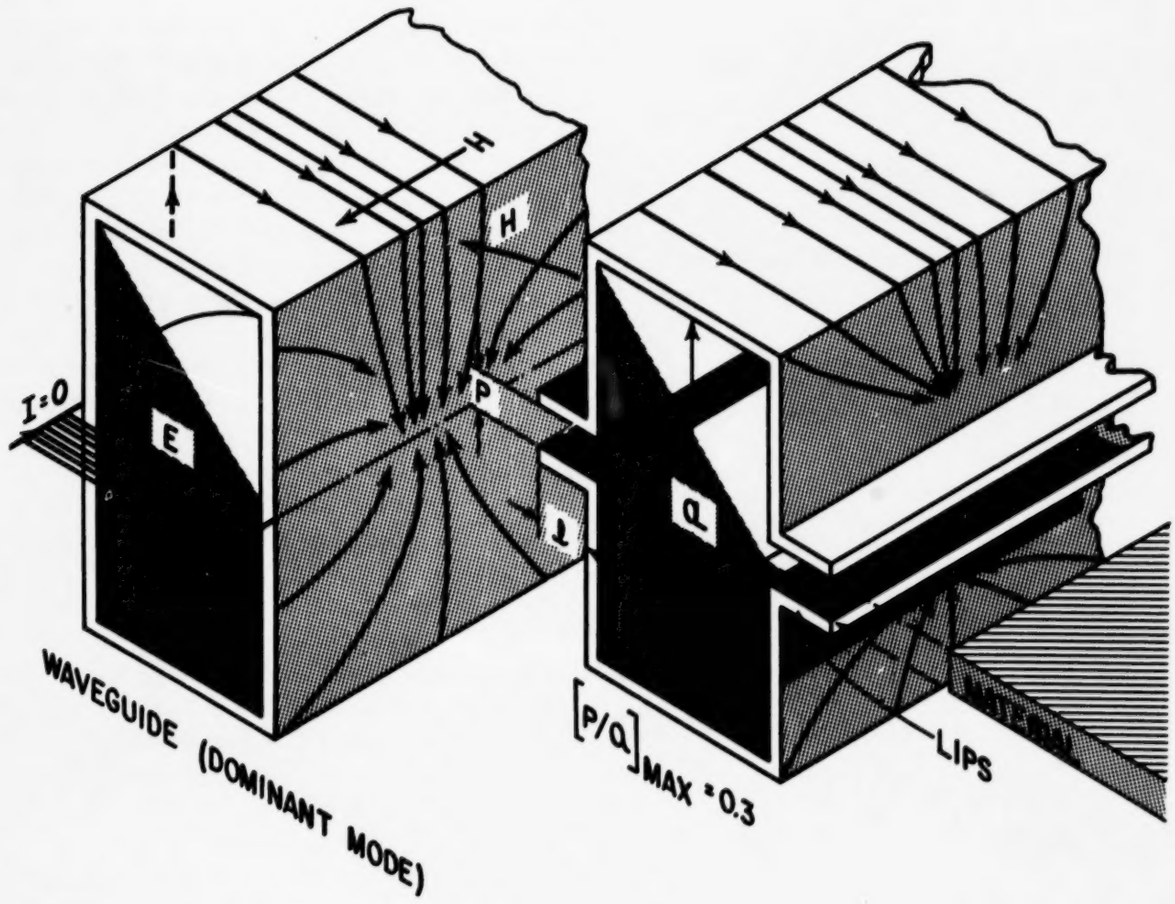

Figure 7. A conventional waveguide carrying the dominant TE mode has the field components shown. The heavy lines are internal surface wall currents induced by the field. A slot cut along the plane of maximum electric field strength does not perturb the wall currents, and the leakage is small for empty slots in this, the plane of maximum heating for a dielectric material. Lips (and filters - see ahead) are used to reduce the leakage in operation.

which probably contains a high velocity air-drying source, becomes a low energy density cavity which feeds the majority of the leakage power back to the material between the waveguides. The designer then has the choice of using wavetraps on the external housing or on the waveguide itself. Generally he uses both.

Similar forms of protection are used with fringe field applicators. A series of bar radiators, enclosed within a cavity, is merely an extension of the slot-array coupling to the cavity wall. It may allow for more controlled use of the power as well as reducing losses through the walls. Designs are highly empirical at this time, but the basic performance of slot arrays is well known (Harvey, 1962). Just as the microwave power-pole and bulk transmission physically resemble the existing power sources, so also do certain applicators. The short circular bar radiator is merely a high frequency immersion heater element which does not rely on thermal conductivity from a hot surface.

4. LEAKAGE: SOURCE AND PREVENTION

Microwave leakage occurs from three principle sources: (a) the cathode structure of generators, (b) applicator doors, and (c) entry, exit, and air ports. These sources apply to all types of applicators. If they are properly designed and installed, flanges and connectors

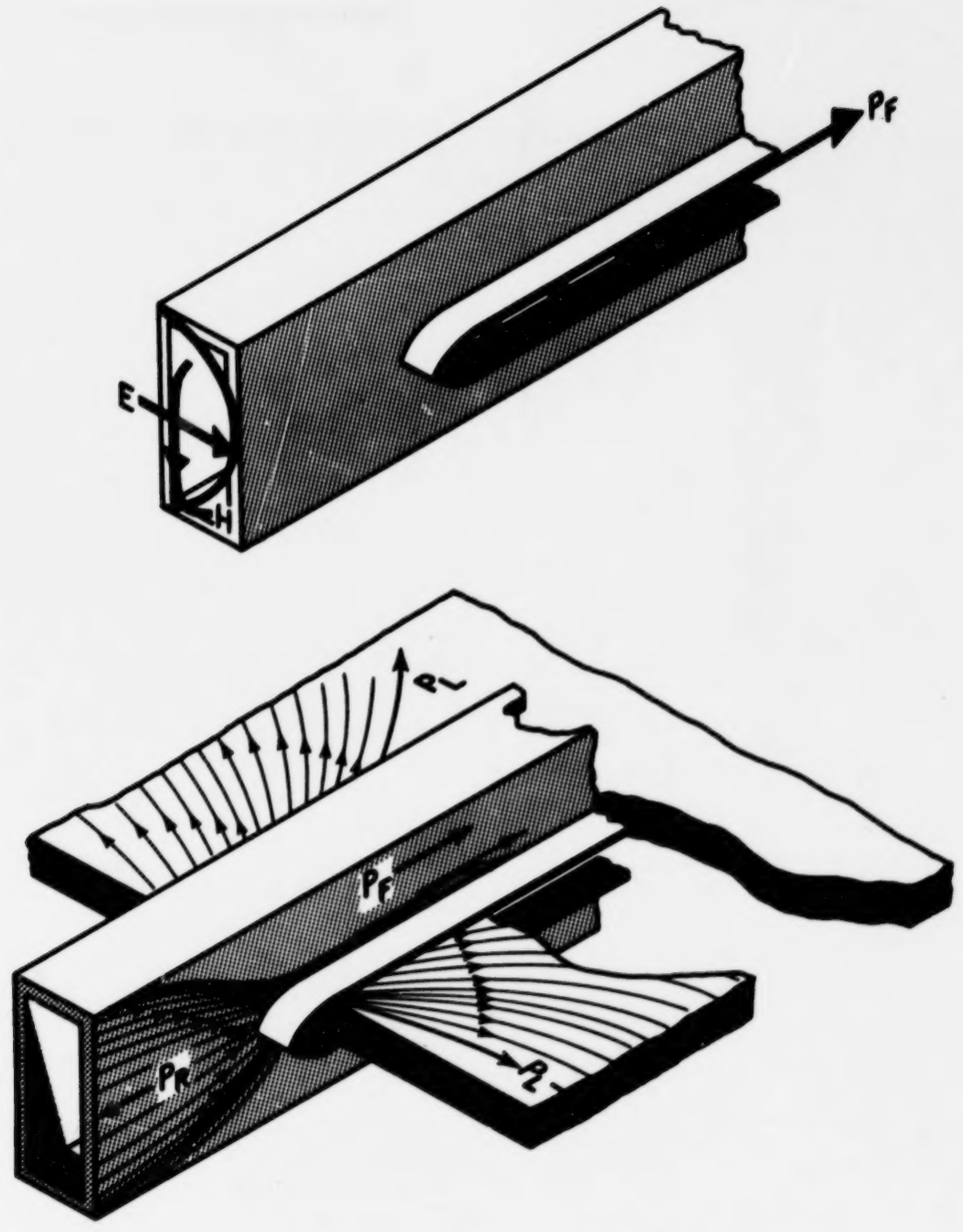

Figure 8. The material can become the means of propagation and the waveguide could then be removed. Lips are carefully designed to taper into the changing field and reduce sparking and associated dangers. This limiting case is usually avoided and cavity heating techniques used instead; however, wet streaks in a material can give rise to a localized effect of this type and external shielding is required.

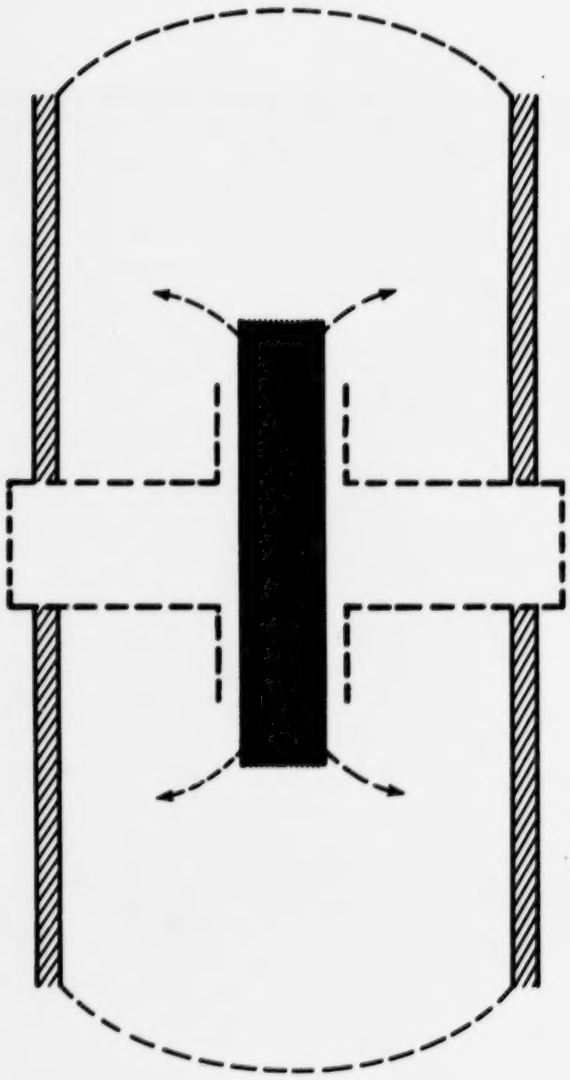

Figure 9. The previous illustrations show that waves can be propagated between the metal boundaries or contained within dielectrics.

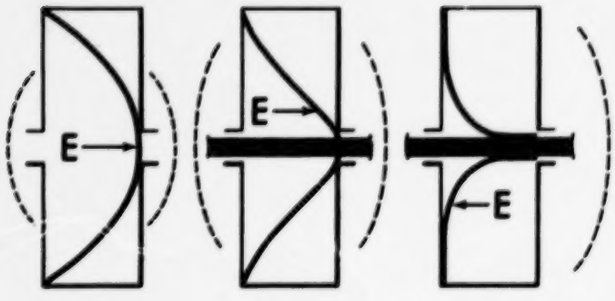

Figure 10. As the dielectric load in a waveguide applicator increases (thickness, moisture content, etc) the sinusoidal E field is compressed into the dielectric, increasing both the power carrying capability of the waveguide and the leakage.

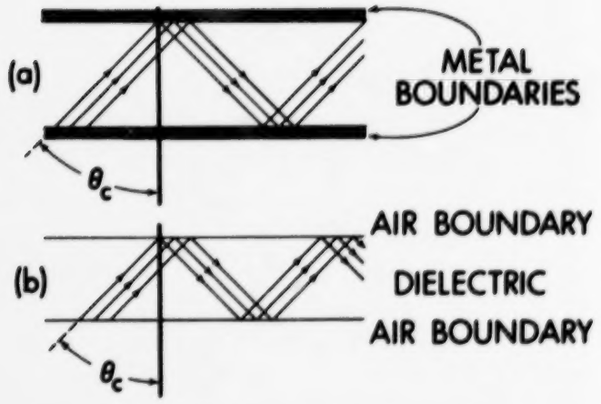

Figure 11. A guided wave can be considered as an interference pattern of incident and reflected plane waves between the boundaries. Dielectric "slab" waveguides can arise in the same fashion. The energy is reflected at the surface if

$$\theta > \theta_c = \sin^{-1}\sqrt{\epsilon'}$$

where ϵ' is the dielectric constant (Ramo and Whinnery, 1953, p388).

seldom give rise to leakage, but even hairline cracks in applicators and waveguide piping can be dangerous. Misuse, such as the removing of interlocks, etc. is the greatest hazard.

To experimenters and service personnel, cathode leakage is by far the most dangerous. It is almost unbelievable that manufacturers do not provide a warning label to this effect. To be safe, the tube and waveguide launching section must be shielded at all times. In view of the air cooling requirements, the most practical approach is to use perforated stainless steel or an aluminum sheet placed within a generator's casing. Twenty gauge or a more finely perforated sheet is used for this purpose as well as for windows (viewing screens) in oven doors.* A typical screen on an oven door may be perfectly satisfactory when monitored by a power meter (most often less than 1 mW/cm²). It must be remembered, however, that the screen is a form of diffraction grating and the leakage will be affected by the presence or absence of a dielectric material. Thus, even with leakage levels measured at less than 1 mW/cm², it is still possible that a child's curious eye may be endangered or that a wet

*Hard and fast rules are not possible. Although a larger mesh would be acceptable at 915 MHz, some additional protection such as a glass screen, is required to prevent the insertion of foreign objects or even fingers.

finger may draw a spark. Consequently, there is a current tendency to avoid the use of screen doors and, instead, to use a solid metal or to install a glass-face wavetrap viewing area.

Applicator doors cause peripheral leakage which must be controlled. Hinges present the greatest problem and the use of a sliding door is favoured, where it is mechanically possible. An invaluable field study by **Surovjec (1967)** has demonstrated the advantage, in practice, of avoiding hinges. Of the units he monitored, 71% released radiation in excess of 1 mW/cm² and 16% were above 10 mW/cm² which is the established limit. Surovjec concluded that door design was the major variable. He believed, as a result of his investigation, that sliding doors were significantly better than those with side or bottom hinge designs. In my experience, bottom hinging has proven to be vastly superior to side hinging and can be designed to restrict leakages to levels which are consistently below 1 mW/cm², if the door is of a heavy construction as illustrated in Figure 5.

The interlock must, in all designs, be an integral part of the door. The microwave circuit must disconnect before the door opens to the point where leakage or sparking can begin to occur. Sparking, a danger in itself, causes metal deterioration, increased sparking, and eventually a severe leakage. Food deposits, in particular fat and oil, further aggravate this situation and there is a strong case to be made for continuous smooth metal enclosures which cannot fill with foreign material. These could easily be cleaned and unaffected by normal wear. The interlock pin must be concealed and should preferably operate the main power line disconnect (except for the filament circuit) as well as the microwave circuit. Lever-pin types and magnetic locks are strongly preferred by designers for these reasons (cf. Figure 5).

5. OVEN DOOR DESIGNS

Some oven door designs are shown in Figure 12. The vertically sliding door (upper left) with a concealed interlock is probably best used in conjunction with a solid metal-to-metal, recessed facing. After five years of use (including laboratory misuse), doors of this type (Figure 6) do not give rise to arcing or leakage levels which are below 2 mW/cm², according to our measurements. Leakage does not occur when the door is opened, due to the double interlock protection. Heavy door designs of this type are realistic on large equipment; on smaller units the problem is greater unless sliding doors are used. The door illustrated in Figure 12 (upper right) uses one form of wavetrap which will be discussed in the following paragraphs. In general, this noncontact seal appears to be less satisfactory; certainly it is difficult to maintain leakage levels below 10 mW/cm², specifically around the hinge side of the trap, after prolonged use. The traps are shorted transmission lines, which can be filled with dielectric material (which ages and warps) or covered by teflon tape (an equally objectionable practice) or left as an almost uncleanable air space (see Figure 13). In some cases observed, the metal bends

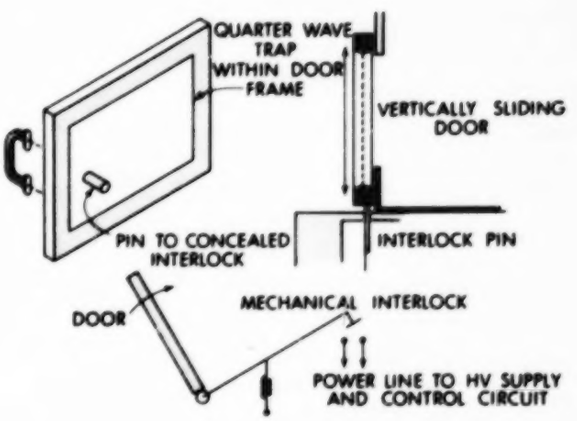

Figure 12. Types of oven door design. Concealed interlocks are essential. Too many can be interfered with on existing models.
Upper left: side opening door with wavetrap; good in theory, poor in practice.
Upper right: with correct design at the interface, probably the best design.
Lower center: first used in Europe; types investigated have proved satisfactory. Note that the double interlock (power line and microwave circuit) is a very desirable feature. The first interlock breaks when the catch is touched, the power line then disconnects as the door opens.

easily. Sprung metal finger stock is also used as a door seal on larger units, but is realistic only if cleaning is regarded as a skilled operation or if regular inspection and replacement are envisioned.

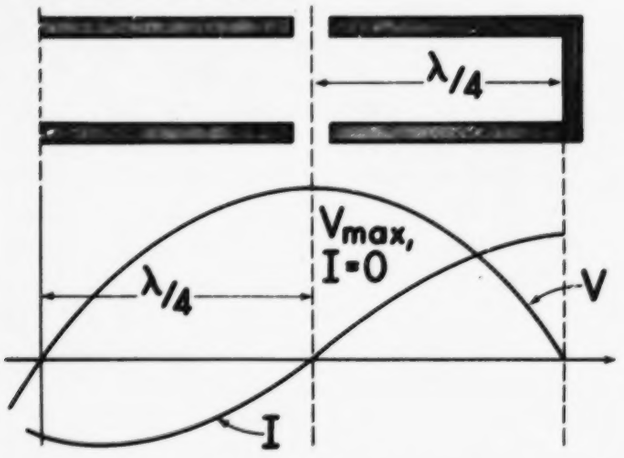

Figure 13. To allow for openings, junctions and doors in microwave power systems, the λ/4 wavetrap is extensively used. A metal discontinuity can be introduced at the plane I = O with minimum leakage.

A major contribution to the evaluation of resonant door seals, of the quarter-wavetrap type, has been made by Crapuchettes (1969) who shows that the presence of an instrument or other perturbing object outside the door tunes the circuit and thereby alters the leakage pattern. Although the door illustrated in Figure 6 has dimensions carefully chosen to minimize leakage, and is effectively a trap and a seal, interactions are mostly reduced by the continuous contact type of design.

A more sophisticated form of the lightweight door wavetrap is shown in Figure 14, the design of which relates directly to the shorted transmission line of Figure 13. In firm contact metal cannot be made, then the metal discontinuity has to occur at a plane of zero wall current. This not only eliminates sparking at the point of contact, but also minimizes leakage. Physically, the quarter-wavetrap is the same as the slot in the rectangular waveguide; the metal discontinuity does not perturb the wall currents induced by the field and therefore does not radiate. However, as with the slotted waveguide, leakage does occur if dielectric materials alter the electrical length of the line or breach the gap.

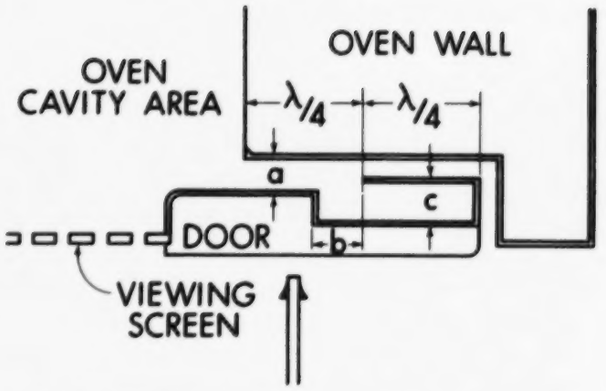

Figure 14. Illustrating a λ/4 wavetrap in a microwave oven door. Typical dimensions are a = λ /36, b = λ /12, c = λ/18 and λ/4 = 31 mm at 2,450 MHz. Plane-faced metal to metal contact may be as good, provided the closing spring is strong. Sliding or horizontally hinged doors are the most satisfactory.

The field strengths in normal heating applications (foods, paper, etc.) tend to be low. Although the term has little applicability, a guideline can be obtained by considering the power fed (or stored) per unit cross section or volume. The order of magnitude is 10 watts/liter for cavities which, in general, gives rise to a low field strength. The presence of a load in the cavity alters this appreciably. This is not the case in, for example, microwave plasma generators, where very high Q (high field strength) cavities are required, or in industrial applications where intense local heating is required to maintain a large temperature gradient (plastic seals, etc.). Openings of the type described are then unsatisfactory and more permanent seals have to be used, or ports have to be made which are waveguides beyond cutoff. These techniques are shown schematically in Figure 15. In ports, leakage increases with the presence of a dielectric.

6. WAVE TRAPS AND PORTS ON CONVEYORIZED SYSTEMS

Electromagnetic energy will propagate down a pipe if the dimensions are large enough, as explained in Section 3. Many trapping systems rely on guiding the potential leakage power back into the product. The liquid coil wavetrap, Figure 16, is extensively used as a shield on conveyorized systems. As a

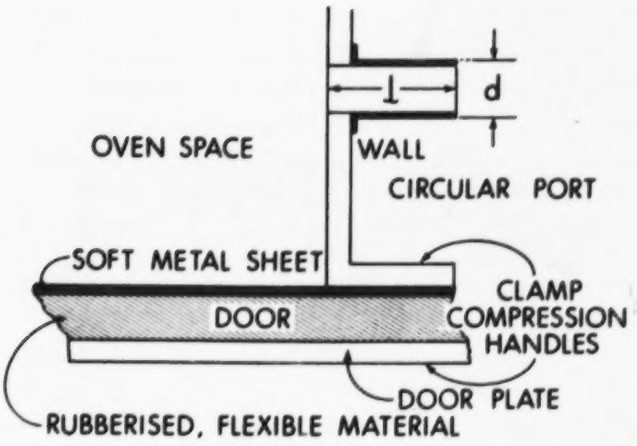

Figure 15. A door safe for experimental design and short term use only, unless extremely well made. Ageing characteristics are poor. The circular port (a waveguide beyond cut off) is extensively used in industrial systems. Note that feeding a material through the port increases the propagation (leakage), and an entry of this type may be dangerous with even a small piece of dielectric material passing through it. Typical safe values empty for air lets, etc. are d = 1.5", ℓ = 3" at 2.45 GHz and 10 watts/liter oven power density. With a 0.5" diameter rod of polyester centrally located in the port, with d = 2.25", ℓ = 3", the leakage is typically 20 mW/cm² at 1" from the port for a 1 KW oven of 75 liter volume heavily loaded. With a 0.5 (ID) plastic water pipe (water temperature at 20°C) through the oven by means of the same ports and oven, the surface wave launched on the water pipe gave a reading of 4 mW/cm² on a densiometer touching the water pipe 3' away from the oven.

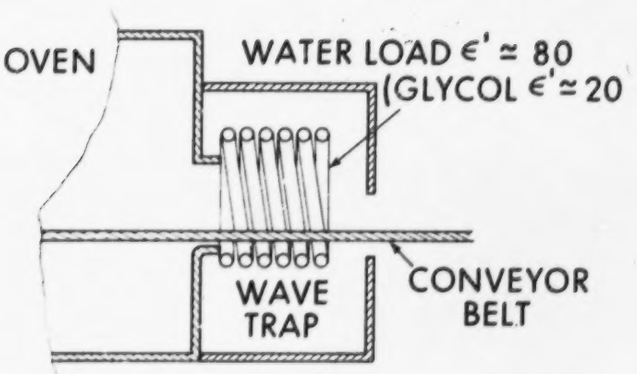

Figure 16. Water coil wavetrap on a conveyorized microwave oven. High reflections occur from water surfaces ($\epsilon' = 80$), but water is a prime absorber. So is antifreeze with a lower reflection and scattering ($\epsilon' \simeq 20$).

final **guard** it is effective, but the absorption per unit length is low; reflection dominates. Small conveyorized systems require more elaborate techniques to reduce the leakage below 10 mW/cm² in operation. This, in itself, is a problem. Research systems and general purpose units will have different leakage patterns according to the material being processed. Further, wavetraps and metal reflectors tend to be narrow band and may not be effective with different tubes, since the center frequency variation, tube to tube, is beyond the bandwidth of some simple traps.

A broadband filter, or wavetrap, shown in Figure 17 has been described in the literature (Püschner, 1966) and is in use. The λ/4 lines interrupt the wall currents of the lowest TE_{mn} modes (for trap heights less than 6 cm at 2,450 GHz, no TM_{mn}* modes can propagate), converting them to the higher TE_{30} mode which is not affected by the stub lines. The λ/4 line presents an infinite impedance back into the main line for the H_{10} mode, thus causing a reflection or mode conversion. The filter is made λ/4 long to the TE_{30} mode, which is reflected; the material exit is then at the plane I = 0, a plane of infinite impedance to the wave. This arrangement is sufficiently broadband to be useful for magnetrons whose frequency swing and change may exceed 20 MHz at 2,450 MHz.

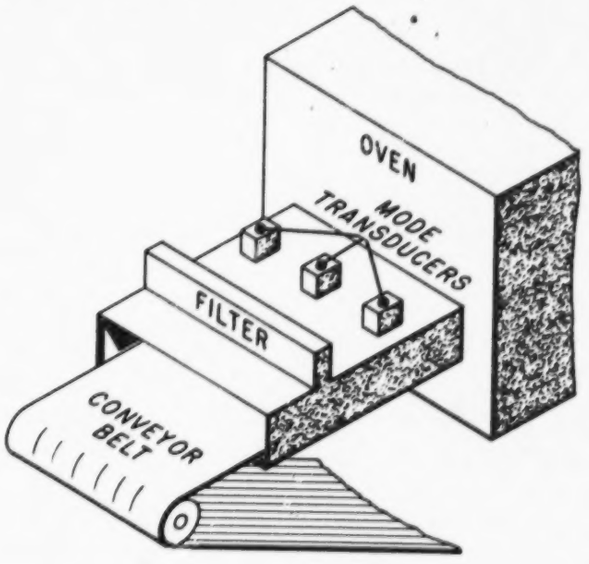

Figure 17. A mode-converting wavetrap.

*TE modes (a transverse electric field) are designated H modes; similarly TM modes are also referred to as E modes.

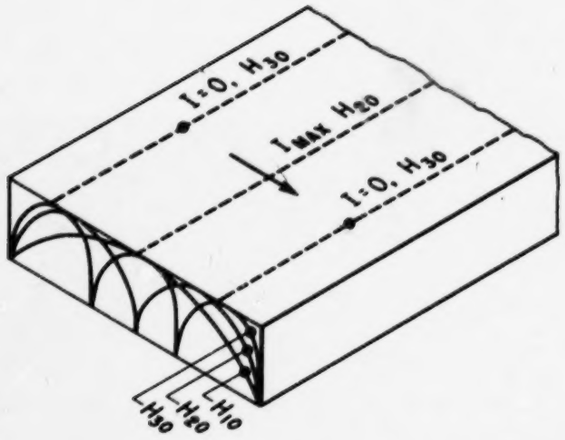

Figure 18. Electric field pattern and wall currents in the filter section.

Figure 19 shows a section view of a mode transducer, filter, and absorber wavetrap. Tuning devices can be included which effectively raise or lower the end wall of the mode converter and filter waveguide sections. A loaded epoxy resin or similar absorbing material (Püschner, 1966) may be used for the final section.

Protection systems of this type have been found necessary for waveguide applicators, either on the lips of the waveguides (filter only) or the inlets and outlets to the oven enclosing a waveguide and hot air system. The dielectric materials to be processed are nonuniform and inhomogeneous from an electromagnetic field point of view; empirical design is essential, and a considerable amount of work has yet to be done to design optimum filters. Cleaning is a problem in the food industry on all except the plastic water coil wavetraps, which now often replace the elaborate metal work required to make filters.

In designing wavetraps, and also in attempting to measure leakage, two additional factors must be borne in mind. The first concerns frequency. The majority of tubes, particularly magnetrons and specifically excluding tuned klystrons, can generate a significant amount of second harmonic energy; i.e. a 915 MHz system may have 5 to 10% of its power at 1830 MHz. This energy will propagate down a waveguide (as an H_{10}-H_{20} mode) and will be absorbed by a material at a greater attenuation rate. It can , however, pass wavetraps designed for the fundamental frequency and may not be recorded correctly on narrow band leakage power meters and sometimes will not be detected at all. Energy propagating in the higher order modes in empty waveguides, for example, readily leaks through the slots. Interference laws (1830 MHz, for example, is not an ISM band) require manufacturers to guard against even low level leakages of this type, but its existence cannot be dismissed, particularly in evaluation studies. The second factor is the relative absorption crossection of an object, relating the unperturbed, plane wave power density to the actual density experienced by dielectric materials of a specific shape in the field (Schwan, 1968).

7. LEAKAGE STANDARDS

Interest in microwave exposure hazards, as well as the biological effects, rose during the last war and was further increased when the available power levels and usage increased. Recent developments and the apparent widespread use of high frequency energy along the lines previously discussed have caused a great concern, particularly in view of the difference between the Russian and U.S. exposure standards (Figure 20). The standard in the U.S., essentially that of the free world, has changed over the years as illustrated in Figure 21, and now appears to be on the verge of dropping again. There are several reasons for the current concern. The Russian standard is based on work that is difficult to reproduce and is subject to many criticisms (Schwan, 1968). However, this is impossible to ignore due to the extent of the studies and the number of workers involved.*

***A detailed review of the literature on biological effects by frequency, mammal, power level and author, was given in Some Biological Effects of Radio Frequency Radiation, Allied Research Associates Technical Report ARA 376-1, for the Office of Telecommunications Management, U.S. Government. A bibliography of recent work has been given by Michaelson (1969).**

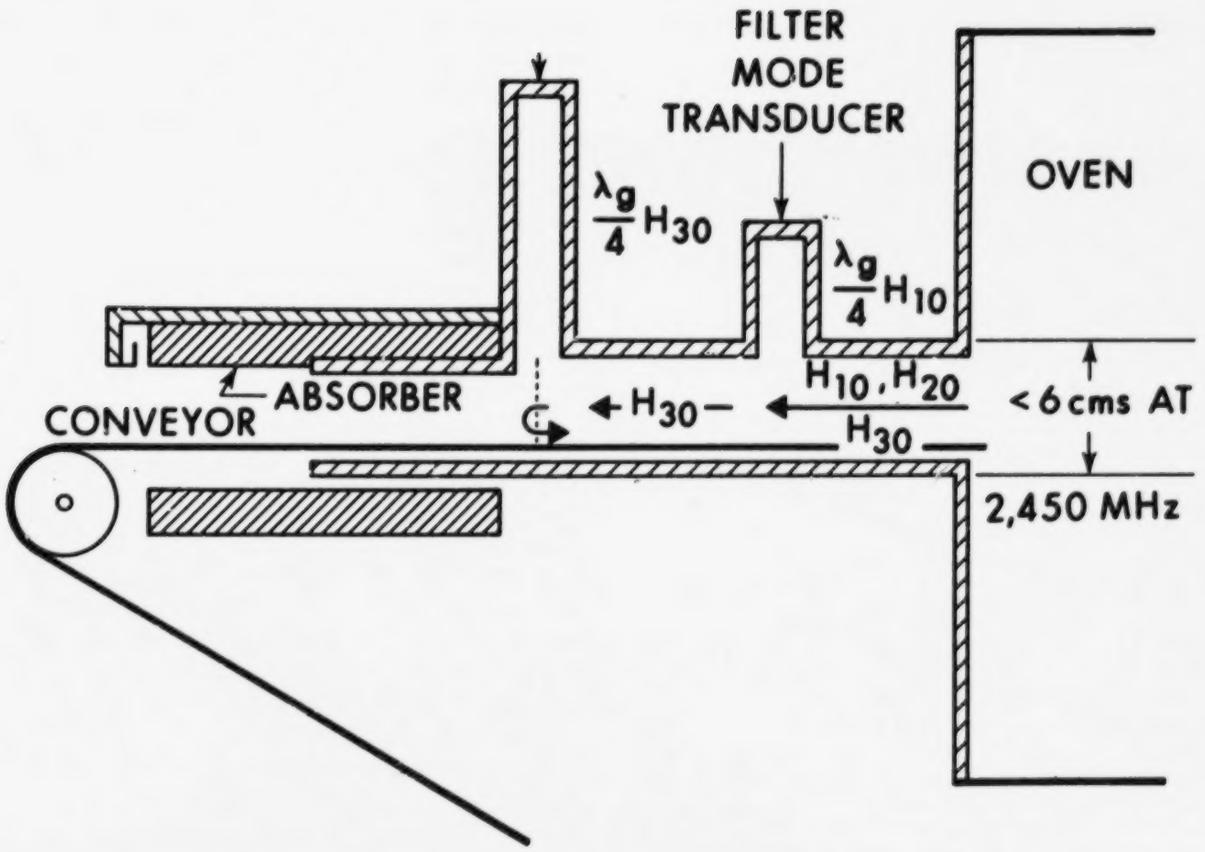

Figure 19. Broad band filters have been designed and used in Europe. The λ/4 lines interrupt the wall currents of the lowest H modes (for trap heights less than 6 cms at 2,450 MHz, no E modes propagate), converting them to the higher H_{30} mode which is not affected by the stub lines (for a λ/4, the impedance is infinite when reflected into the main line). These stubs act as mode converters. The H_{30} mode is a reflecting filter and effectively the exit port is at a plane of zero current. This arrangement is sufficiently broad band to be usful for magnetrons whose frequency swing and change may exceed 20 MHz at 2,450 MHz.

Reliable instrumentation for measuring leakage is just beginning to be developed (Section 8). Microwave heating equipment is sold beyond recall, thereby suggesting that tight control in manufacture is essential. In industrial applications there are no realistic means of controlling misuse by ignorance. In a detailed analysis, Mumford (1968, 1969) has shown that there is a strong argument, in terms of total body radiation, for leakage levels not to exceed 1 mW/cm² at ambient temperatures above 75°F. In initiating investigations into effects and hazards, the importance of the "Radiation Control for Health and Safety Act of 1968" cannot be over-emphasized.** Most equipment designers who are familiar with the literature and aware of the lack of specific data on pulse and CW effects, auditory perception (Frey 1962, Sommer and Von Gierke, 1964) and the possible behavioral effects, are striving for levels below 10 mW/cm²

If a 1 mW/cm² level were to become a legal requirement, industrial equipment costs would increase by perhaps 10%. It would

**At the fourth IMPI Symposium (Edmonton, 1969), a discussion of U.S. Public Law 90-62 was given by H.J. Reehen and D.J. Nelson, Bureau of Radiological Health, Division of Electronic Products (Paper DA7).

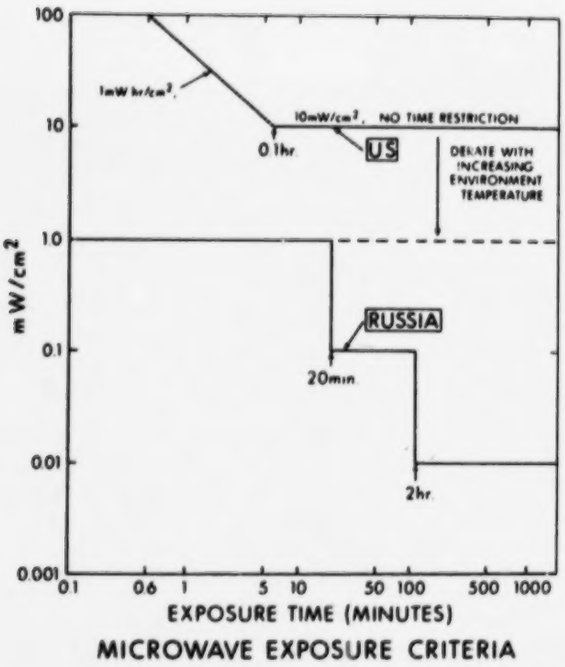

Figure 20. A comparison of U.S. and Russian Standards on Microwave Exposure. Calculations made by Mumford (1968) support the argument that in terms of the temperature humidity index of the human body, the 10 mW/cm² level should be revised to 1 mW/cm² general exposure for ambient temperatures above 75°F.

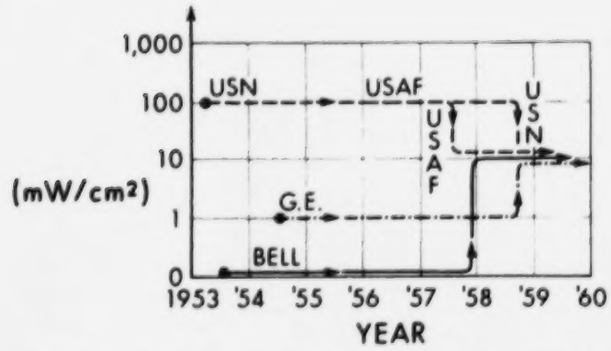

Figure 21. Safety standards adopted by various organizations have changed. They may change again as more fundamental data on biological effects is obtained.

entail a more extensive use of protecting barriers, wavetrap lengths would increase, and certain small domestic ovens would become unmarketable. It must be borne in mind, for example, that a leakage level of 5 mW/cm² at the surface of a large exit port falls below the recommended 1 mW/cm² a short distance from the original point of measurement. One of the long term space saving advantages of microwave drying lies in the vertical tower concept. This flexible type design is illustrated in Figure 3. Automation and modern control techniques are beginning to require fewer people to operate a processing system and, for this same reason, close continuous handling by operators is no longer essential in well designed systems.

The adequacy of the original 10 mW/cm² is questioned in our minds because of the results of the Russian work and also because of the inadequacies of the maintenance and control of equipment currently in use. However, unnecessarily conservative standards (based on a lack of biological study data) would place unfair restrictions on manufacturers and hold back technological advances in areas of prime industrial importance. As Michaelson (1969) states, a more precise definition of the microwave hazard is required; biological effects must be investigated further and the public protected. However, complete protection requires education and this education is particularly important in the areas of equipment service and maintenance.

Only thermal effects have been considered in the determination of the present U.S. standard for Maximum Permissible Exposure (MPE) based on the work of Schwan and Li (1953, 1956). Data obtained from animal experimentation have indicated that levels around 100 mW/cm² were required to produce hyperthermia and eye damage. Subsequently, Ely and Goldman (1957) determined 150 mW/cm² as the threshold for eye damage, and 5 mW/cm² for testicular damage at 3 GHz. This and subsequent work (Carpenter, et al., 1967) have been performed on animals at various frequencies. Models of the human body have been studied in terms of penetration depth; the only experiments on human beings reported in the U.S. literature relate to the supposed non-thermal auditory response (Frey, 1962), who has calculated that only a narrow band of frequencies around 1 GHz can penetrate the human brain to any significant extent (about 10% of the incident energy). **It is significant that this work has**

been almost ignored by other writers and no attempt has been made to pursue Frey's calculations. Life scientists are finding many interactions between magnetic fields and biological systems and biomagnetism alone is now a major area of research (Kolin, 1968). Increased use of microwave power is apparent in medical treatment (diathermy) and diagnostics, and with it, the needed research on biological effects becomes more crucial since that knowledge alone can determine hazard levels at different frequencies, including RF.

8. LEAKAGE MEASUREMENT

Advances in the uses of microwave power have accelerated the development of leakage detectors. At the beginning of this decade commercial instruments were unsatisfactory (Miller and Sheftman, 1961). Crapuchettes (1969) has found that, of the presently available instruments, the Narda 8100 is highly satisfactory. Two other instruments are shown in Figure 22.

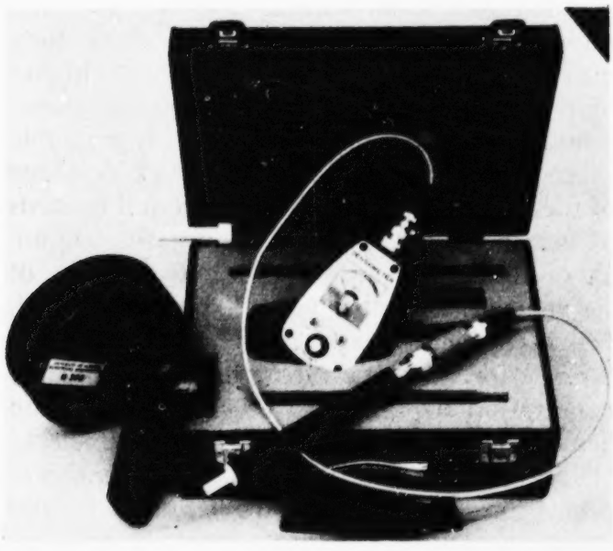

Figure 22. Two portable leakage detectors.
Right: Magnetic AB, Sweden.
Left: Ramcor.
Both operate at 915 and 2,450 MHz. Broad band instruments detect power at the harmonic as well as fundamental frequencies.

Crapuchettes (1969), in his detailed evaluation of the majority of the commercial units now in use, has found that instruments can perturb the leakage field by effectively tuning the wave trap circuit, if they are used in close proximity to the door seal. Thus the leakage is dependent upon the environment. This tuning phenomena is in itself a strong argument against noncontact resonant seals (and lightweight doors) and gives rise to considerable doubt about the validity of many leakage measurements which have been reported.

The requirements of a leakage power meter (or densiometer) are thus very stringent. It must meet the following criteria: (a) be suitable for close proximity recording without perturbing the true field, (b) be either frequency independent over a wide range (as in the case of the Magnetic-AB instrument) or usable at all the ISM frequencies and their second harmonic by a clearly marked switch, (c) eliminate field polarization uncertainties and record the total electric field, and (d) must be free from cable pick-up and other interference effects.* In practice instruments are required to read over a range of 0.1 to 100 mW/cm^2 The particularly important scales are obviously the 0-0.2 and 0-10 mW/cm^2 since most readings are at levels between these values. These levels are recorded by the Narda 8100 unit with accuracies of ± 10%. A typical oven manufacturer's specification (proposed) is 1 mW/cm^2 at 5 cm from a domestic type oven on production line tests. It does not immediately follow that this ensures, for example, less than 10 mW/cm^2 to a curious eye inspecting the door catch or that the door cannot be damaged in use. However, it may be a reasonable standard and, as such, certainly requires accurate leakage instrumentation to levels below 1 mW/cm^2, meeting the requirements listed above and allowing for more detailed investigations.

Leakage instruments are calibrated against standard gain (precision) antennae in free space. This equipment, although readily

***Crapuchettes (1969) gives the draft of the American Home Appliance Manufacturers' Specifications for Microwave Survey Meters (Table 1).**

available in most microwave laboratories, is bulky and requires skilled operation. Consequently, ruggedness and long term calibration accuracy are essential for an instrument that is going to be used by television and electronic repair organizations who will not calibrate the sensing unit every few months. For this reason, thermistors, a common heat sensing element, may be unsatisfactory for long term, general use.

The thermistors (temperature sensitive resistors) are fed from dipole antennae - usually on printed circuit board. Polarization effects are reduced by using dipole pairs at right angles; however, the instrument has to be manually positioned to obtain the maximum reading. Another principle has been developed in England by the Wayne Kerr organization. The incident radiation in their instrument is absorbed by a sphere which is coated with a resistive film. The air within the sphere expands with the heat created by the absorbed wave. The pressure difference between the air in the coated sphere, and an identical but uncoated sphere alongside it, is measured and calibrated against known incident power densities. The pressure recording mechanism is a diaphragm whose position is recorded on a capacitance bridge. The output signal from the bridge is linearly proportional to the incident power density. A frequency range of 0.4 to 40 GHz is obtained, with scales 0-3 mW, 0-10 mW and 0-100 mW.

Glow tubes are sensitive to peak rather than average power and are therefore useful for determining leakage changes due to slow mode-stirrer (impeller) action. However, these tubes are not yet reliable over long periods of time. When it is new, a glow tube (such as the Philips 4662) is extremely useful for determining leakage zones and peak points, but actual measurements must be taken with a calibrated instrument.

Field strength measuring instruments can be used for far field studies, but are not practical for close-up leakage recording around doors and ports. Used in conjunction with a spectrum analyzer, it is possible to determine harmonic leakage as well. At the second harmonic frequencies (e.g. 1780-1880 and 4800-5000 MHz), acceptable interference levels are slightly below the level considered hazardous and are a function of the area and the composition of the radiating surface. At frequencies below 0.4 GHz, field strength measuring techniques have to be used. Values of 195 V/meter and 0.5 ampere-turns/meter correspond to 10 mW/cm^2 in free space. Apparently only the U.S.S.R. and Czechoslovakia have established permissible levels in the lower frequency ranges: 20 V/m, 0.1-30 MHz; 5 V/m, 30-300 MHz (U.S.S.R.) and 10 V/m, 0.01-30 MHz (Czechoslovakia).

9. CONCLUSIONS

The ability to generate and transmit continuous microwave power at the megawatt level heralds a new era in the utilization of electronic energy. **Every effort must be made to ensure its safe use through education and further research on the health implications of exposures. Basic research into the biological effects of microwave power must be supported.** The current work of Tanner et at. (1969), Birenbaum and Rosenthal (1969), is of vital importance, as is that of the other study groups planning to work with the higher mammals which have electromagnetic cross-sections involved which more closely resemble those of man. Only from a detailed knowledge of the biological effects can the actual hazards to health be determined. The relative significance of pulse and continuous power, of frequency and time, must be considered. Equally, from the electromagnetic standpoint, every effort must be directed to pursuing the penetration depth, effective cross-section and heating studies of Frey (1962), Schwan and Li (1953) and Mumford (1968). Evaluation programs on equipment (Suroviec, 1967) and instruments (Crapuchettes, 1969) deserve essential support. And, collectively, our responsibility is also to ensure that the user understands the danger of deliberate misuse as well as the long term advantages of the correct utilization of electronic power equipment.

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